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Cost-optimized design of a dual-mode diesel parallel hybrid electric vehicle for several driving missions and market scenarios

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HIGHLIGHTS

- Tools for cost-optimized design and performance of HEVs.
- Dual-mode parallel hybrid architecture.
- Optimal control strategy based on fuel consumption, NOx and battery aging.
- Impact of cost definitions on HEV design.
- Impact of fuel & battery price and battery life on cost-optimized design of HEVs.

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ABSTRACT

The present study has focused on the refinement of a previously developed tool for the optimization of the layout of hybrid electric vehicles and on its application to a newly proposed non-plug in parallel hybrid vehicle, which has been equipped with a planetary gear set and a single-speed gearbox positioned between a compression ignition engine and a permanent magnet electric machine. This vehicle is capable of torque-coupling and speed-coupling between the engine and the electric machine, and for this reason has been referred to as a "dual-mode vehicle".

The tool performs a bi-level (nested) coupling of design and control strategy optimization, and is able to identify the optimal design of each hybrid vehicle by minimizing the powertrain costs over a 10-year time span. The vehicle design determines the size of battery, engine and electric machine, as well as the values of the speed ratio of each power coupling device. Different powertrain cost definitions, which account for the production costs of the components and the operating costs related to fuel consumption and battery depletion over the lifetime of the vehicle, have been proposed. The latter cost contribution depends directly on the control strategy adopted to manage the power flow between the electric machine and the engine, as well as on the selection of the transmission gear. The optimal control strategy has been identified using a specifically developed fast running dynamic programming-based optimizer, which minimizes an objective function over a given training driving mission.

The performance of the dual-mode vehicle with the optimal layout has been investigated in detail over several driving missions and compared with that of more traditional hybrid vehicles equipped with either a speed coupling device or with a torque coupling device, as well as with a conventional reference vehicle.

Moreover, several sensitivity analyses have been carried out in order to investigate the impact of the cost definition, of the objective function and of the training driving mission on the powertrain design and on its performance (fuel economy, pollutant emissions, battery management).

Finally, different market scenarios have been explored, in terms of fuel price, battery life and battery cost, and their effects on the identification of the optimal design, as well as on the performance of the resulting vehicles, have been analyzed.

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Nomenclature

Acronyms

AER	All Electric Range
AMDC	Artemis Motorway Driving Cycle
AUDC	Artemis Urban Driving Cycle
BLC	Battery Life Consumption
BU	Battery Usage
CO_2	Carbon dioxide
DMV	Dual Mode Vehicle
DP	Dynamic Programming
D1	1.7 L Euro 5 GM diesel engine
D2	1.3 L Euro 5 GM diesel engine
E	Engine
EGR	Exhaust Gas Recirculation
EM	Electric Machine
ES	Engine State
EV	Electric vehicle
FC	Fuel consumption
FD	Final Drive
GB	Gear Box
GN	Gear Number
HEV	Hybrid Electric Vehicle
J	Objective function
NOx	Nitrogen oxides
PF	Power Flow
PG	Planetary Gear set
PI	Performance Index
SC	Speed Coupling
SCV	Speed Coupling Vehicle
SOC	State Of Charge
TC	Torque Coupling
TCV	Torque Coupling Vehicle
TM1	Internally-developed Training Mission (1)
TM2	Internally-developed Training Mission (2)
TM3	Internally-developed Training Mission (3)
TR	Transmission

Variables

C	cost [$]
C_{bat}	battery capacity [A h]
E	energy [J]
I_{wh}	wheel moment of inertia [kg m^2]
I_{bat}	battery current [A]
$\dot{m}_{fc}$	fuel mass flow rate [kg/s]
$\dot{m}_{CO_2}$	CO_2 mass flow rate [kg/s]
P_{fd}	final drive power [W]
P_v	vehicle power [W]
R_{wh}	dynamic radius of the wheel [m]
S_{es}	set of discrete values of the state of the engine
S_{gn}	set of discrete values of GN
S_{pf}	set of discrete values of PF
S_{soc}	set of discrete values of SOC
t	time [s]
T	torque [N m]
u	control strategy
V_v	velocity [m/s]

Greek symbols

α	sub-control variable of PF
λ	battery life consumption [A h]
λ_r	battery life residual [–]
Λ	battery life [A h]
ρ	fuel density [kg/m^3]
σ	severity factor related to battery aging [–]
τ_{sc}	speed ratio of the speed coupling device [–]
τ_{tc}	speed ratio of the torque coupling device [–]
ω	angular speed [rad/s]

1. Introduction

1.1. Background

In recent years, the automotive industry has dedicated a great deal of effort to developing innovative technologies for the realization of green vehicles characterized by low CO_2 and pollutant emissions [1]. Battery equipped electric vehicles (EV) have only a battery as the energy source, and traction power is provided by one or several electric machines. These vehicles are highly energy efficient and feature zero tailpipe emissions, while the well-to-wheel emissions depend on the electric energy production process. If the electric energy is derived from a renewable source, well-to-wheel emissions can be reduced to a great extent [2,3]. However, these vehicles have not been successful so far on the market, because of the higher costs, the added weight of the batteries, the reduced load capacity, the limited driving range and the lack of recharging infrastructures [4]. Fuel-cell electric vehicles are still in their early stages of development, as the fuel-cell technology is not yet mature, but they have shown an interesting long-term potential [2,5]. Hybrid electric vehicles (HEVs) offer improved fuel economy and lower emissions than conventional vehicles and they can take advantage of existing fuel infrastructures. HEVs are provided with two energy sources, i.e., a battery and a fuel tank, and they are equipped with a conventional thermal engine and one or several electric machines. A significant advantage of HEVs, compared to battery EVs, is that they offer the possibility of increasing the driving range, due to the presence of the thermal engine. However, the driving range in pure electric mode is much lower, as a consequence of the installation of smaller battery packs. HEVs lead to a reduction in fuel consumption (FC) and CO_2 emissions, compared to conventional vehicles, mainly due to the reduction in engine size, to the possibility of recovering the kinetic energy through regenerative braking, to the implementation of the Stop–Start mode and to the possibility of optimizing the power flow from the engine and electric machines [6]. Several studies have demonstrated the capacity of the hybrid technology to reduce CO_2 emissions in developing countries [7,8], which are expected to contribute significantly to the greenhouse gas emissions from the transport sector in the near future. Moreover, a recent study has shown that the life cycles of CO_2 emissions of modern HEVs are shorter than those of conventional vehicles [9]. HEVs are therefore considered to represent one of the most promising technologies. A classification of HEVs can first be made considering whether the batteries can be charged from an electric grid (plug-in HEVs) or not (non plug-in HEVs). Plug-in hybrid electric vehicles use both electrochemical energy storage and a conventional fuel to overcome the drawbacks of EVs and HEVs. Plug-in HEVs have the potential of further reducing fuel consumption, as well as pollutant and CO_2 emissions, compared to non-plug-in HEVs [10–12]. However, they are usually equipped with larger battery packs than non plug-in HEVs, in order to allow a higher all-electric range (AER) to be obtained. Moreover, the incremental battery cost of plug-in HEVs might not be counterbalanced by the savings in fuel cost, as was shown in [13].

HEVs can also be classified according to their architecture. Many different hybrid architectures, whether of a series, parallel